An Autonomous Data Recorder for Field Testing

Joseph A. Carroll and Michael D. Fennell
Tether Applications 1813 Gotham Street Chula Vista, CA 91913 619-421-2100 tether@home.com

KEYWORDS
Inter-modal, Data Recorder, Autonomous

INTRODUCTION
Progress in the development of miniature sensors, microprocessors, compact nonvolatile “flash” memory, and battery technology allows the design of sophisticated miniature autonomous data recorders for a wide variety of inter-modal transportation applications.

In some cases, requirements for data recorders are well known or already specified by law. However, in new applications for data recorders, it is not always apparent what parameters need to be measured, nor with what frequency or precision. It may be useful in early field tests to collect more data than might be justified in an operational system, to allow assessment of what data is actually most useful. Since early field tests often involve retrofit into existing vehicles, it is also useful for a field-test recorder to have its own sensors, to simplify installation. This can also enable “fleet surveys” in which a few recorders are moved from one vehicle to another. Small autonomous data recorders are also useful for gathering data during vehicle testing. In some cases they may find use supplementing conventional data recorders, because they can be distributed throughout a large vehicle with little or no wiring.

Tether Applications has designed a Small Intelligent Datalogger (SID) with a variety of unusual features, including multiple on-board sensors, on-board alarm clocks for low-duty-cycle operation, and several serial-interface networking options. Its original purpose was as the core of some very small, low-cost, low-power spacecraft, but it also appears relevant for a variety of applications requiring small autonomous data recorders. It appears particularly well suited to early field-testing, where programming, installation, data recovery, and data analysis are likely to cost far more than purchase of the recorders themselves.

MAIN SECTION

Numerous applications exist for miniature autonomous field data recorders. SID appears most suited to applications where:

1. Developing data recorder specifications for new applications requires gathering field data to assess which parameters are needed, and at what frequency, precision, and overwrite-interval.
2. Running wires throughout the vehicle or connecting to existing sensors or electrical systems is time-consuming, unsafe, or not allowed, but field data must be collected. An example is adding new sensors during a vehicle test program. Using a small autonomous datalogger with its own sensors and batteries could reduce vehicle down-time. This may significantly speed up the test schedule.
3. A backup data collection system is desirable in some operational vehicles that already have data recorders. One case is collecting data after failure of primary vehicle power. A small low-powered battery-powered system could supplement the primary data recorder with pressure, temperature, acceleration, and other data. A related issue is that a recorder that can process data onboard to provide useful short and long-term summaries for maintenance (eg, fatigue life indicators; changes in resonant frequencies, etc.) may supplement existing mandated data recorders.

DESIGN PHILOSOPHY

Our hardware design philosophy was to include all features we need for an initial list of applications, plus as many other features useful to related applications as we could accommodate without driving the system size, cost, or power requirements. Since "one-size fits all" solutions often fit nothing well, we designed the board for easy expansion via stacking boards, rather than trying to fit everything interesting on the board itself. The board can be assembled with all or a subset of its nominal sensor suite.

The board uses commercial off the shelf parts and is assembled using standard techniques. It includes board-wide latchup detection and protection. This is not needed for terrestrial applications, but may be useful in high-altitude aircraft. To improve reliability in high-vibration environments, electrical interfaces to other boards or devices use short ribbon cables that are soldered in place, instead of connectors. In cases where connectors are needed, they can be installed on ribbon cables or stacking interface boards.

Most components are surface-mount type, for reduced board size, higher reliability, and greater thermal robustness. (Surface-mount assembly puts the chips and board through a thermal torture-test much worse than it will generally see in service, except in a vehicle fire.) But the oscillator crystals use through-hole cylindrical packages and compliant potting, for better shock and vibration tolerance than available with existing surface-mount crystals. The board should handle shocks and accelerations >1000 gees. Vibration limits will vary with resonances in the supports but should be quite high. Components larger than 0805 (0.080"x0.050") are leaded, to increase robustness against board flexing and thermal cycling. For good heatsinking even at high altitudes or in a vacuum, heat-dissipating chips like the regulators are near corner mounting holes, and internal copper layers are used as "thermal ground planes" in those areas.

SID is designed around a highly integrated Hitachi SH7045F 32-bit RISC microcontroller. Hitachi SH microcontrollers are used as embedded controllers in numerous applications ranging from digital cameras to heavy off-road trucks. The SH7045F includes 256 Kbytes of non-volatile "flash" program memory, 4 Kbytes of SRAM, an 8-channel 10-bit A/D converter, and a variety of other intelligent peripherals. The board has another 1Mbyte of SRAM and 8 Mbytes of serial flash memory for data storage. An 11-wire programming interface allows users to make in-circuit upgrades of the software in the flash program memory. Stacking expansion boards can add up to 4 Gbytes of additional flash memory if needed.

SID is 10x55x85 mm and weighs <50 grams without batteries or external packaging. This is light enough that in some cases, SID might be installed by being taped into place, using a tape like 3M VHB foam tape. SID consumes ~70 mA at 5.5V to 10V when running at 7MHz, with all sensors on. This allows a standard 46-gram 9V alkaline "transistor battery" to power the board for 6-8 hours of "on time." Hitachi specifies the CPU only over the -20^{o}C to 75^{o}C temperature range, but prototype boards have worked properly even at -80^{o}C, and we are using it at less than half its rated maximum speed.

SID has 3 independent alarm clocks. They allow SID to turn itself on and off on an arbitrary schedule, to see if the host vehicle is in use. This can greatly extend main battery life in low-duty-cycle vehicles such as general aviation aircraft. SID can turn on, initialize, and check its sensors within 20 ms, so even frequent status checks can be compatible with long battery life. SID can also can be awakened by an external active-low signal or by battery installation, and SID can determine what triggered its wakeup.

Perhaps SID's most unusual feature is its two independent 512-byte blocks of dual-port battery-backed SRAM that can be powered, addressed, and accessed (read or write) by an external "1-wire" network even when SID is off. Each board also has 2 independent 1-wire network controllers. As a result, one board can read, write, and pass 512-byte messages between a large number of other boards on each of two networks, whether those boards are on or off at the time. We call this network concept "DreamNet."

ON-BOARD SENSORS

The on-board sensors measure temperature, ambient pressure, 3-axis acceleration, and 2-axis angular rates. (The board is scarred for the 3rd rate axis, but the chip is not yet available, so we provide connections for an off-board sensor.) The acceleration sensors are typically used in automobile airbag controllers, and the angular rate sensors are used for image stabilization in video cameras. Their drift is far too large to use for guidance (~1deg/sec after correction for temperature effects), but adequate for detection of turns, skids, and vehicle roll. The onboard sensor characteristics are listed below in Table 1. Analog sensor outputs are digitized by the SH7045F with 10-bit resolution, typically at 100 Hz. The digitized data can be scaled, offset, and compensated for thermal effects, using calibration data specific to each sensor on each board.

On-board Sensor	Range	Comments
Digital Temperature Sensor	-55 to 125°C	Allows compensation for temperature-induced sensor errors.
Ambient Pressure Sensor	0-15 psia	Portless sensor (ie, senses air pressure where board is)
X and Y axis accelerometer	±50 g	Software can also select a ±5 g range in real time
Z axis digital accelerometer	±50 g	Sensors also available in other ranges (±5 to ±100 g)
X and Y axis rate gyro	± 180 deg/s	Large thermal drift, mostly correctable.
Z axis rate gyro	TBD	Now off-board; may be available on board by end of 1999

Table 1: On board sensors

INTERFACES TO OFF-BOARD SENSORS

Besides the above on-board sensors, SID provides interfaces for various off-board sensors. The most interesting one for vehicle data recorder applications may be a “frame-grabbing” imaging interface to a new CMOS imaging chip from Photobit. This interface allows SID to “grab” up to 5 video-quality frames at rates up to 30 Hz. After that, SRAM will be nearly full and images must be overwritten, compressed, and/or saved to flash memory. One way to use this imaging interface is to continuously grab images at ~2 per second, and save the 5 most recent images (and some later ones) if a crash occurs.

External Sensor	Number	Range	Comments
Thermocouples or photodiodes	16	Variable	Set scaling resistor and software for type used.
Digital temperature sensors	64	-55 to 125°C	2 sets of up to 32 “party-line-wired” sensors.
Event-detectors	4	N/A	Uses 4 photopairs to detect door status, etc.
CMOS imaging camera	1	Variable	Photobit PB159 CMOS 384x512 imaging chip.
Z axis rate gyro	1	±180 deg/sec	Sensor must be mounted normal to board.

Table 2: Interfaces to off-board sensors

OTHER EXTERNAL INTERFACES

Besides the on-board sensors and interfaces to off-board sensors, SID has various uncommitted resources that may be useful in various applications. They are listed below. All are brought out to ribbon-cable interfaces around the edge of the board. Some are arranged to ease specific applications. For example, the ribbon cable interfaces for two of the serial ports also have unregulated power-switches associated with them, so SID can switch on other serial-interface devices such as telemetry transmitters or GPS receivers.

External Interface	Number	Comments
Bi-directional 0-5V serial ports	4	Muxed; up to 230 kb/s asynch or 860 kb/s synch, if f=7MHz
Interrupts	8	Active low inputs, with 4.7K pullup resistors to 5V
0 to 5V analog input lines	4	10-bit A/D; can each be read at up to ~10 kHz or muxed 8 ways
Timer I/O pins	8	Event-timing; pattern generating, etc.
Other I/O port pins	8	Can be written to or read under DMA control if desired
Other available pins	24	Two 8-bit VHC output latches plus 8 other misc. I/O functions
40V, 1A power switches	6	Power supply is separate but ground is common with board
Other lower-power switches	8	To switch power to expansion boards, DreamNet networks, etc.

Table 3: Other external interfaces

EXPANSION BOARDS

SID allows easy expansion using stacking boards connected by short 10-wire ribbon cables, with mechanical support and heatsinking at the corners. A 55x55x4 mm add-on memory board can add 256 Mbytes of flash memory to the 8 Mbytes on SID itself, and up to 16 such boards can be used if necessary. The 4 unused analog lines can be expanded to 32 muxed channels (with signal conditioning) on a similar board, and an imaging mux board allows the board to select and grab frames from any of 8 cameras. The flash and imaging boards should not add much to average power consumption, because they can operate in standby mode most of the time. But they will increase peak consumption, requiring some attention to battery impedance. (This can be a serious constraint at low temperature, especially near the end of battery life.) Other special-purpose expansion boards can be designed as needed, to use various combinations of the uncommitted resources listed in Table 3. For example, the 0-5V serial ports can be converted to RS232 or RS422; IR or CAN interfaces can be added; and suitable connectors can be added as needed. One other interesting expansion option is a solar cell array. A 55x85 mm array of cells in full direct sunlight can provide roughly enough power to run SID. If connected to rechargeable batteries and mounted under an untinted windshield, such an array may provide enough power for some modest-duty-cycle applications like general-aviation aircraft.

Board	Comments
32 channel analog expansion	Uses 4 free A/D channels + 4 octal muxes + signal conditioning
Flash memory expansion	Up to 16 boards can be added, each with sixteen 16Megabyte chips.
Imaging multiplexer	This allows SID to select and grab frames from any of 8 cameras.
Solar cell array	55x85 mm array may be enough to recharge batteries in some cases.

Table 4: Typical expansion boards

PROGRAMMING

Early in our development effort we realized that in many low-volume applications, programming will be the dominant life-cycle cost. So we focused on making the board reflect the structure and capabilities of the CPU, to minimize the need for customizing or extending the software development tools made for the

SH CPU itself. The SH family was designed for efficient execution of C code. Hitachi, GNU, and Green Hills provide C and C++ compilers. Stenkil Engineering's "MakeApp" program is useful for configuring the many intelligent peripherals on the SH7045F. Much of the code development and testing can be done on Hitachi's SH7045EDK Evaluation/Development Kit. That kit includes an interface board and software that allow any PC to reprogram the SH7045F's flash program memory through a serial port. SID uses the same interface board and software for in-circuit program updates, with a special adapter cable. If desired, we can develop application-specific programs for users or assist them in their programming efforts.

CURRENT STATUS

We have built and tested prototypes of the 3 major parts of the board (the sensor section, the digital core, and the power management section). We have laid out 90% of the components and traces for the final board, and expect to have the layout completed and printed circuit boards fabricated before the end of April. Assembled prototypes should be available in May, along with simple programs now being developed on the SH7045EDK. Price for one board with a sample datalogging program will be ~$3K.

CONCLUSIONS

Many applications exist that can benefit from small autonomous data recorders. This new data recorder provides a combination of on board sensors and external interfaces that make it suitable for use in a wide variety of applications, particularly development-intensive applications like early field testing.

ACKNOWLEDGEMENTS

This work was partially supported by a NASA Marshall SBIR Phase 2 contract and a study contract from NASA Ames Research Center.

REFERENCES

Hitachi SH7040 Series Hardware Manual, Version 3.0.
MakeApp for the SH7040 family, available from www.stenkil.com (demo version is free)
Dallas Semiconductor DS2404 Econoram Time Chip datasheet, February 1998.
Photobit PB-159 DX CMOS Active Pixel Digital Image Sensors datasheet, Ver. 3.0, August 1998.

BIOGRAPHIES

Joseph Carroll has worked as a consultant on microcomputer design for remote datalogging and applications of tethers in space since 1981. He founded Tether Applications in 1989 to commercialize a concept he developed at Energy Science Labs under NASA SBIR funding. Tether Applications was the prime hardware contractor to NASA Marshall Space Center on the SEDS-1 and SEDS-2, (Small Expendable-tether Deployment System) flight experiments. SEDS-1 demonstrated controlled deorbit without rockets, using a 20 km tether; SEDS-2 demonstrated passive stabilization of a pair of spacecraft. Tether Applications has also provided tether deployer hardware to Johnson Space Center, the Naval Research Lab, and the European Space Agency. Mr. Carroll has a BA from Catholic University of

America (1969). He was awarded a NASA Public Service Medal in 1994 for his work on the SEDS 1 and 2 projects.

Michael Fennell has worked on materials and electronics development projects since 1983. From 1995 to 1996 at Volution Inc. he contributed to the development of a multi-sensor fume, smoke, and fire detector for Navy ships. He was a consultant for Tether Applications for several years, and has been an employee for a year. He has a BA (1983) from Swarthmore College and an MS (1988) from the University of California, San Diego.